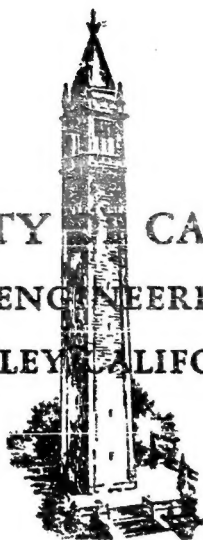


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THE SNOW EMISSIVITY METER
AND ITS USE IN EVALUATING THE EMISSIVITY OF
ICE, FROZEN GROUND AND OTHER MATERIALS

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Introduction

The research program reported herein was conducted under the auspices of the Snow, Ice and Permafrost Research Establishment of the Corps of Engineers of the U. S. Army as a part of Contract DA-11-190-ENG-3. An objective of this contract is the measurement of the total emissivity and absorptivity of wet and dry snow, ice, frozen ground and materials used in the arctic regions. To accomplish this, an instrument, the Snow Emissivity Meter, was designed utilizing a mirror to focus the incident energy upon a thermopile detector and an ideal radiator for controlling radiation from the surrounds. The preliminary results obtained from laboratory testing are reported herein.

Description of Apparatus

The basic design was previously described in the Progress Report for the year June 27, 1952 to June 27, 1953 of the Snow Characteristics Research Project, Series 62, Issue 1, dated June 27, 1953. In brief, a double walled hohlraum through which isothermal fluids may be circulated is placed over the sample surface. The energy emitted by the sample surface passes through an opening in the upper wall of the hohlraum and is intercepted by a first surface spherical mirror which focuses the energy upon the thermopile detector. The detector is a wire wound silver-constantan thermopile $3/8$ inches wide and has approximately 60 active differential junctions. The receiver strip is 0.33 inches in diameter, the diameter of the image of the opening in the hohlraum. A schematic diagram of the optical system and construction details of the whole instrument are given in Figures 1 and 2.

An energy balance upon the sample and a radiation shield used as a zero reference, yields the following equation:

$$\frac{K(\Delta V)}{F_{RM}} = \epsilon_s \sigma \left[(T_h^4 - T_s^4) - F_o (T_h^4 - T_l^4) \right] + \sigma \epsilon (T_l^4 - T_h^4) \quad (1)$$

where

- C = constant, defined by equation (2)
- e = emissivity or emittance
- F = geometrical shape factor
- K = calibration constant of the detector - BTU/hrft²/mv
- T = temperature - °R
- V = detector output - mv
- Δ = difference
- C = Stefan-Boltzmann constant - 1.72×10^{-9} BTU/hr °R⁴

Subscripts

- h = hohlraum
- c = sample surface with respect to opening in upper surface of hohlraum
- RM = receiver with respect to mirror
- s = sample surface
- x = upper and lower cylinders and upper surface of hohlraum with respect to mirror
- l = shield

The value of C is defined by

$$C = 1 - F_o + \frac{F_x}{F_{RM}} = F_h + \frac{F_x}{F_{RM}} \quad (2)$$

The derivation of these equations is shown in Appendix I.

Equation (1) may be solved for the emissivity of the surface, thusly:

$$e_s = \frac{\frac{K(\Delta V)}{F_{RM}} - C(T_l^4 - T_h^4)}{(T_h^4 - T_s^4) - F_o(T_h^4 - T_l^4)} \quad (3)$$

The term ΔV is the difference obtained when viewing the sample surface and the reference shield. The constants shown in the above equations were:

$$C = 1.149$$

$$F_{RM} = 0.197$$

$$F_0 = 0.0262$$

$$\frac{F_x}{F_{\text{SH}}} = 0.175$$

$$F_h = 0.974$$

The temperature of the hohlraum was measured with four Cu-Co thermocouples equally spaced on the inner walls. The shield temperature was measured with a Cu-Co thermocouple peened to the upper surface of the radiation shield. For laboratory purposes, thermocouples were also placed in the detector holder and in the air column. The sample surface temperature was determined with thermocouples embedded in the sample along the surface. This insured that the leads were in an isothermal environment and reduced heat losses from the thermocouples.

The hohlraum was maintained in an isothermal condition by circulating water through the double walls. The temperature was maintained at a level between 60 and 70°F. Experience showed that this level provided the most stable convective conditions within the air column surrounding the detector. This temperature did not cause the samples to melt as the base was well insulated from the sample by the bakelite ring.

The instrument was set in a deep freezer. The level of the top of the freezing compartment was approximately the level of the slot in the lower cylinder provided for insertion of the reference radiation shield. The upper cylinder was therefore exposed to the warm ambient room air. This procedure was found to be necessary to reduce "fogging" of the mirror and assisted in stabilizing the air column within the instrument.

The detector was calibrated by placing the instrument over the opening of an ideal radiator. The hohlraum was a cylinder immersed in a water (or ice) jacket, blackened on the inside and having dimensions of 5 inches inside diameter and 6 inches deep. These dimensions combined with the emissivity of the internal coating provided the requisite conditions for Planckian radiation.

(Buckley 1934). The constant was determined for a source temperature range of 20 to 70°F and a curve of the resultant calibration is shown in Figure 3. The maximum deviation of the experimental calibration from the mean value of 30.6 BTU/hrft² mv was less than 1.0 percent.

Results

A. Soils

	Moisture Content Percent Dry Wt. (approximately)	Range T _s °F	Range T _h °F	e _s
Soil 1	50 (saturated)	22.2 - 27.4	67.4 - 73.3	0.93
	31	11.2 - 19.8	67.5 - 72.5	0.93
	20	7.0 - 24.0	67.2 - 72.0	0.94
	10	11.2 - 27.9	65.3 - 70.3	0.96
	.5 (dry)	39.5 - 55.8	64.9 - 80.4	0.94
Soil 2	40 (saturated)	15.2 - 31.3	61.7 - 69.6	0.92
	25	11.0 - 23.4	67.0 - 73.0	0.93
	16	11.8 - 28.4	65.8 - 71.0	0.94
	9	17.0 - 28.8	64.9 - 66.4	0.94
	.5 (dry)	38.6 - 66.3	65.6 - 66.3	0.95

Soil 1 and Soil 2 were different samples obtained from a field in the Lafayette, California area. Each value of e_s is the average of a minimum of five measurements.

B. Ice

Range T _s °F	Range T _h °F	e _s
0.6 - 18.9	69.0 - 73.5	0.97

The value of e_s is the average of 10 readings.

C. Miscellaneous

Description	Range $T_{s,OP}$	Range $T_{b,OP}$	ϵ_s	No. of Measurements	Remarks
Flat white paint on polished aluminum	17.8 - 29.7	69.4 - 72.1	0.91	3	
Flat black paint on polished aluminum	13.5 - 24.4	70.0 - 71.2	0.88	3	
Magnesium Oxide on polished aluminum	16.6 - 18.4	69.1 - 70.9	0.64	3	
Magnesium Oxide over flat black paint on polished aluminum	27.8 - 36.1	73.2 - 73.9	0.91	3	0.006" thick
Aluminum foil	16.6	72.5	0.01	1	
Aluminum foil coated with vinyl chloride plastic < 0.001" thick	7.5 - 21.4	72.1 - 72.4	0.06	3	

Discussion

A. Results

The order of magnitude of the results obtained checked those previously obtained and published in standard texts on heat transfer (e.g. Introduction to Heat and Mass Transfer, E. R. G. Eckert, McGraw-Hill, 1951). The small variation of the emissivity of soil with different moisture contents may be attributed to experimental variation or it may be considered to be an effect caused by filling the intergranular spaces with ice (or water). The voids between the particles in dry soil may act as small ideal radiators with an effective emissivity of 1.0. Filling these with ice which has an emissivity of 0.97 could therefore account for the reduction of the emissivity of the sample as a whole. The variation noted is of the order of ± 2 percent and for engineering applications, the mean value should be satisfactory.

The miscellaneous surfaces were selected to provide confirmation of other measurements or concepts regarding the long wavelength emissivity of these materials. Thus, the value obtained for the aluminum foil coated with vinyl

chloride plastic partially substantiates in magnitude the spectral reflectance measurements reported in the previously noted Progress Report (Gier, Dunkle 1953) page 45. From the spectral data, the coating may be seen to have reduced the reflectance to a value between 90 and 95 percent. The effect is approximately constant within the spectral limits of the reflectance data. The emittance of this material was 0.06 within a temperature range of 7.5 to 21.4°P and for these temperatures, approximately 50 percent of the energy of a Planckian radiator is beyond the limit of the spectral measurements, i.e. 15 microns. Hence, a qualitative conclusion may be made that the effect of the coating is constant from 15 microns to 25 microns (say). The value obtained for aluminum foil was only approximate as the energy emitted by the sample was very small. Consequently, the error involved was larger than desired. The direction of the error should be toward a smaller value than reported.

The emittances of white and black paint were taken to demonstrate again that white paint is "blacker" than black paint at long wavelengths. This further confirms the results reported in terms of spectral reflectance. The results obtained with magnesium oxide were further confirmation of the spectral measurements. In the case of magnesium oxide, the interpretation of the data is complicated by the two effects of increasing thickness and transmission. An increase in thickness will increase the reflectance by transmission and inter-reflection. Also, transmission will lower the value for the sample on polished aluminum and raise it for the black paint background sample. Thus, the increase in emittance of the sample on black paint may have been caused by either or both increased thickness and absorbing background (Gier and Dunkle, 1953).

B. Use of Equipment

The only important change that was found to be necessary was the replacement of the nylon-glass strings supporting the detector holder with nichrome wire. The nylon-glass material was found to stretch and deteriorate rapidly

under the conditions of operation. After that change, no further trouble was encountered. The heat losses through the wire did not affect the calibration of the detector.

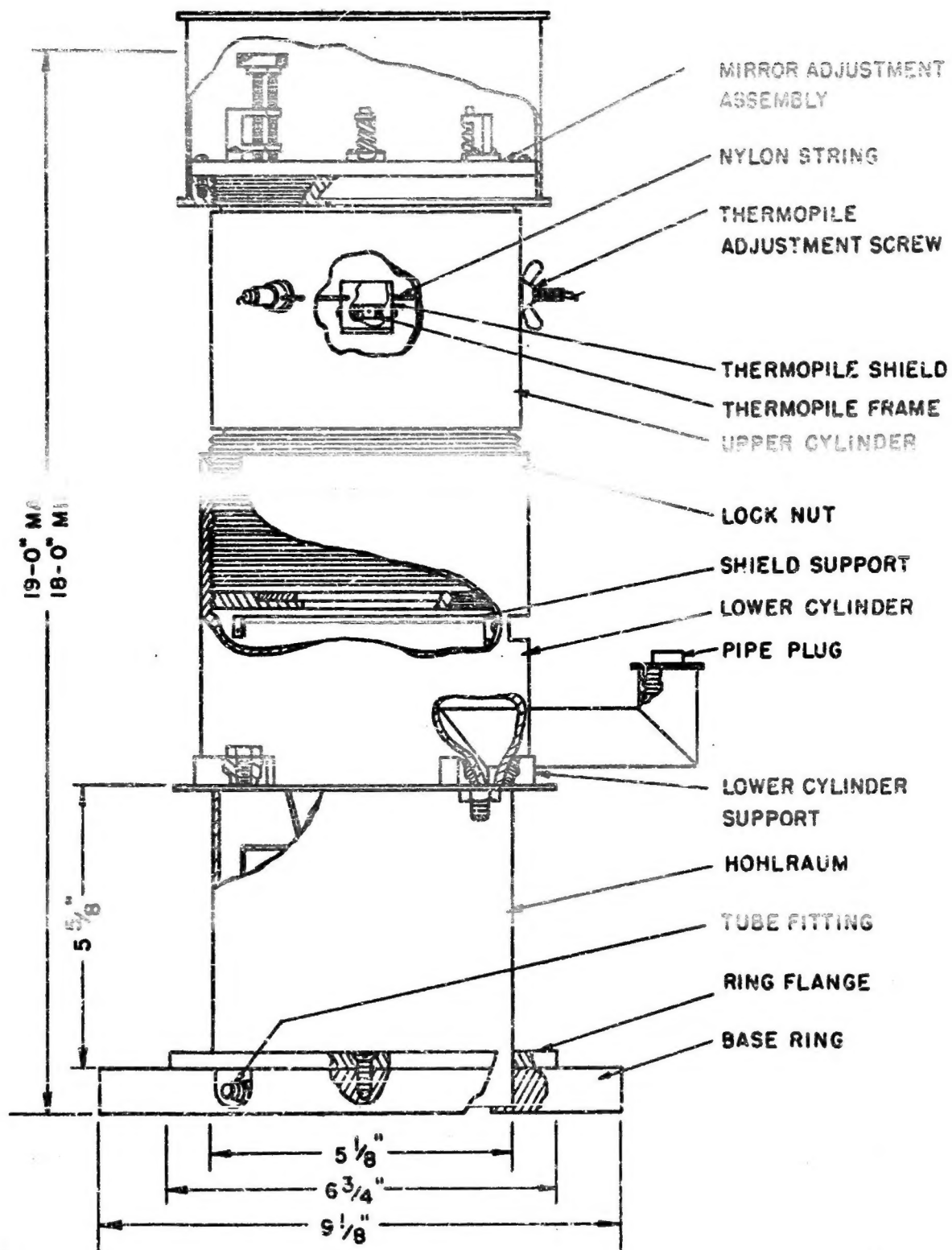
As originally planned, the instrument was intended to be used in the field, i.e. out in the open. With the present equipment, this method of operation is not amenable to field usage because the instrument requires a pump for circulation of isothermal fluid in the walls of the cavity and a potentiometer sensitive to one microvolt for measurement of the detector output. The instrument could be used in a laboratory located in the field wherein electrical energy and water were readily available. In this latter case, the samples would have to be in close proximity to the laboratory.

The convection currents in the instrument must be stabilized much in the manner described. Use in the open would interfere with this pattern and seriously alter the calibration of the detector. Fogging of the mirror would also constitute a problem.

The use of a coolant other than water was attempted. Liquid nitrogen was tried and found to be impractical. Fortunately, the presupposed necessity of reducing the radiation emitted by the hohlraum was found to be unwarranted (Gier and Dunkle 1953). Reliable and consistent results were obtained with a hohlraum temperature between 60 and 70°F. The change in spectral distribution between 0°F (say) and 60°F would be very small and the results obtained with the higher temperature should be equally reliable at the lower temperature.

REFERENCES

- Buckley, H. (1934) On radiation from inside a circular cylinder, Philosophical Magazine and Journal of Science, vol. 17, (113), series 7, p. 576.
- Gier, J. T., R. V. Dunkle, et al. (1953) Progress report for the year June 27, 1952 to June 27, 1953, Contract No. DA-11-190-ENG-3, Snow Ice and Permafrost Research Establishment, U. S. Army Corps of Engineers. Series No. 62, Issue 1, June 27, 1953, Institute of Engineering Research, University of California (Berkeley).



SNOW EMISSIVITY METER

Figure 1

SNOW EMISSIVITY METER RAY DIAGRAM

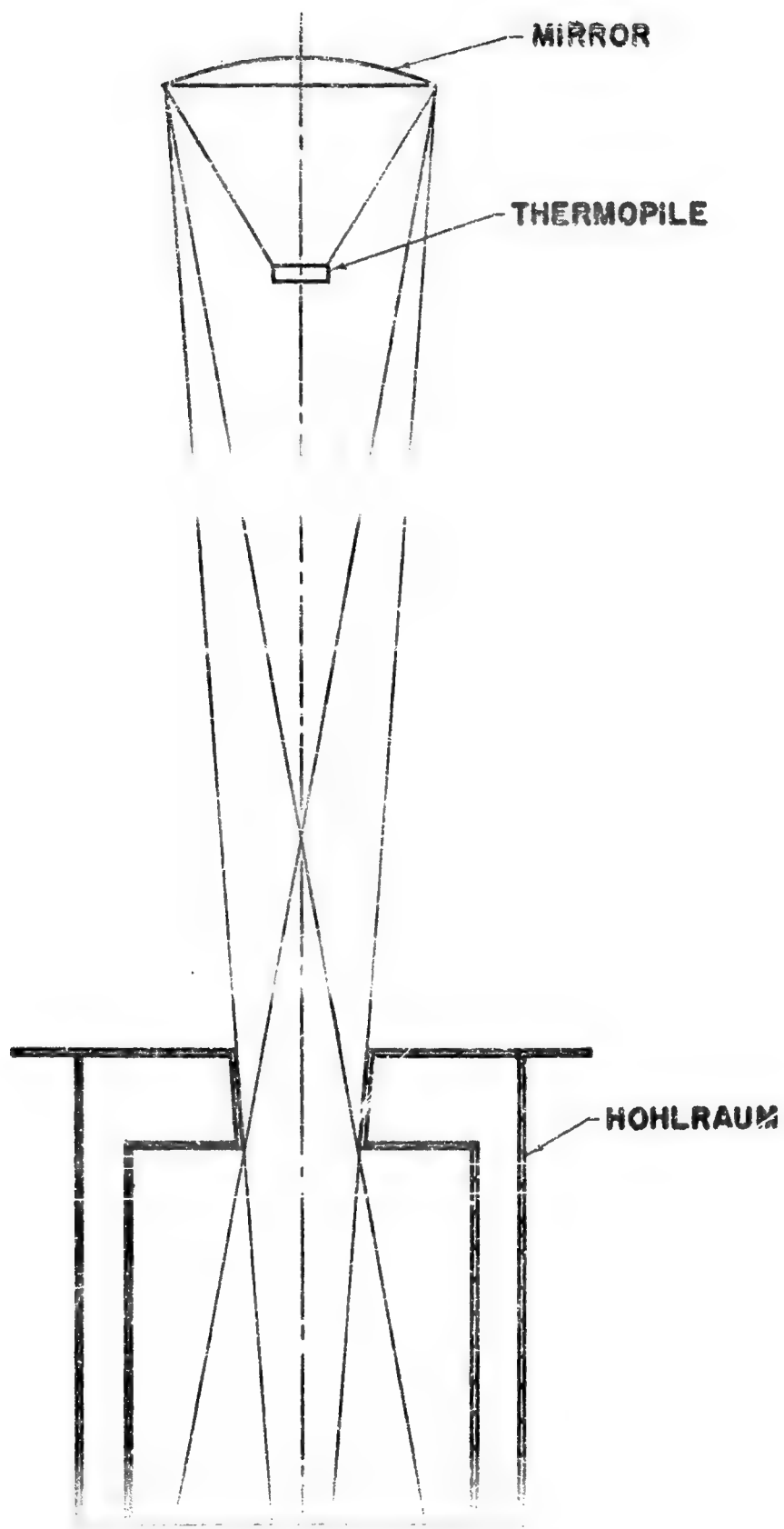
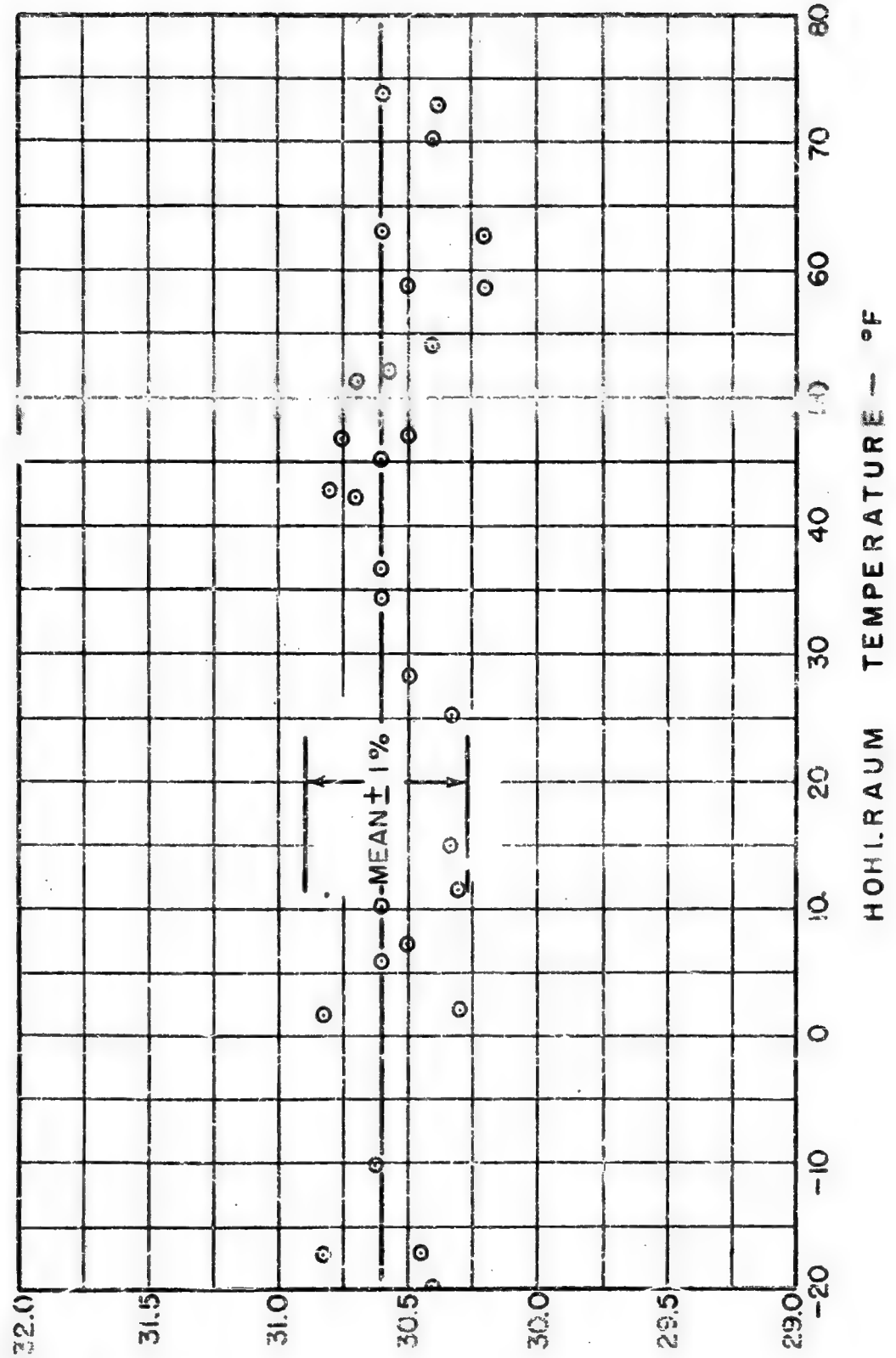


Figure 3

CALIBRATION OF THERMOPILE AS A FUNCTION OF HOHLRAUM TEMPERATURE



APPENDIX I

Derivation of Equations

A. Viewing the sample

$$G_s = K V_s + \sigma F_{RM} T_{Ra}^4 = \sigma F_{RM} e_s T_s^4 + \sigma F_x T_h^4 + F_{RM}(1-F_o) \sigma (1-e_s) T_h^4 + F_{RM} F_o \sigma (1-e_s) T_1^4 \quad (1)$$

B. Viewing the shield

$$G_b = K V_b + \sigma F_{RM} T_{Rb}^4 = \sigma F_{RM} T_1^4 + \sigma F_x T_1^4 = \sigma F_{RM} e_s T_1^4 + (1-e_s) \sigma F_{RM} T_1^4 + \sigma F_x T_1^4 \quad (2)$$

Subtracting equation (1) from (2)

$$K(V_b - V_s) + \sigma F_{RM}(T_{Rb}^4 - T_{Ra}^4) = \sigma F_{RM} e_s (T_1^4 - T_s^4) + (1-e_s) \sigma F_{RM} (T_1^4 - T_h^4) - F_o F_{RM} (1-e_s) (T_h^4 - T_1^4) + \sigma F_x (T_h^4 - T_1^4)$$

$$\begin{aligned} \frac{K}{F_{RM}} (\Delta V) + \sigma (T_{Ra}^4 - T_{Rb}^4) &= \sigma e_s (T_1^4 - T_s^4) + (1-e_s) \sigma (T_1^4 - T_h^4) - F_o \sigma (1-e_s) (T_1^4 - T_h^4) \\ &+ \sigma \frac{F_x}{F_{RM}} (T_1^4 - T_h^4) \\ &= \sigma e_s \left[(T_h^4 - T_s^4) - F_o (T_h^4 - T_1^4) \right] + \\ &\sigma \left[1 - F_o + \frac{F_x}{F_{RM}} \right] (T_1^4 - T_h^4) \end{aligned}$$

$$\frac{K}{F_{RM}} (\Delta V) + \sigma (T_{Ra}^4 - T_{Rb}^4) = \sigma e_s \left[(T_h^4 - T_s^4) - F_o (T_h^4 - T_1^4) \right] + \sigma C (T_1^4 - T_h^4) \quad (3)$$

The assumption is made that $T_{Ra} = T_{Rb}$: i.e. readings are taken rapidly enough so as to preclude a change in the detector temperature. Therefore the final equation is

$$\frac{K}{F_{RM}} (\Delta V) = \sigma e_s \left[(T_h^4 - T_s^4) - F_o (T_h^4 - T_1^4) \right] + \sigma C (T_1^4 - T_h^4) \quad (4)$$

where

$$C = 1 - F_o + \frac{F_x}{F_{RM}} \quad (5)$$

The symbols have the following meaning

- C = constant defined by equation (5)
- e = emissivity or emittance
- F = geometrical shape factor
- G = irradiation incident upon thermopile detector
- K = thermopile detector constant - $\text{BTU/hrft}^2/\text{mv}$
- T = absolute temperature - $^{\circ}\text{R}$
- V = thermopile output - mv
- σ = Stefan-Boltzmann constant - $0.172 \times 10^{-8} \text{ BTU/hr } ^{\circ}\text{R}^4$
- Δ = difference

Subscripts

- b = conditions obtained when viewing shield
- h = hohlraum
- o = opening in hohlraum upper surface (sample surface with respect to opening)
- R = receiver
- RM = receiver with respect to mirror
- S = sample surface
- x = upper and lower cylinders and upper surface of hohlraum with respect to mirror
- l = shield

APPENDIX II

Estimate of Experimental Errors

An estimate of the errors involved may be made by assuming

$$(a) \quad T_1^4 \approx T_h^4$$

$$(b) \quad T_h^4 - T_s^4 \approx 4\left(\frac{T_h + T_s}{2}\right)^3 (T_h - T_s)$$

Assumption (a) is experimentally a valid assumption. Assumption (b) is valid within less than 10 percent if $T_h \leq 2 T_s$. This is within the experimental conditions.

Equation (4) may therefore be differentiated logarithmically to give (assuming $F_{RM} = \text{constant}$):

$$\frac{dK}{K} + \frac{d(\Delta V)}{\Delta V} = \frac{de_s}{e_s} + 3 \frac{d(T_h + T_s)}{(T_h + T_s)} + \frac{d(T_h - T_s)}{(T_h - T_s)} \quad (6)$$

For calibration of the detector, an ideal radiator was used, i.e., $e_s = 1$.

Therefore the error in the calibration constant was

$$\frac{dK}{K} = \frac{d(\Delta V)}{\Delta V} + \frac{de_{s_{ideal}}}{e_{s_{ideal}}} + 3 \frac{d(T_h + T_s)}{(T_h + T_s)} + \frac{d(T_h - T_s)}{(T_h - T_s)} \quad (7)$$

Assuming the following conditions

ΔV	$\approx 0.200 \text{ mV}$	$d(\Delta V)$	$= 0.0005$
$e_{s_{ideal}}$	≈ 1.00	$d(e_{s_{ideal}})$	$= 0.005$
T_h	$= 520^\circ\text{R}$	dT_h	$= 1/4^\circ\text{R}$
T_s	$= 480^\circ\text{R}$	dT_s	$= 1/4^\circ\text{R}$

Then the value of $\frac{dK}{K}$ is

$$\frac{dK}{K} = .0025 + .005 + .006 + \frac{1/2}{40}$$

$$= .026$$

$$\approx 2.5 \text{ percent}$$

The error in measured e_s under the same conditions would be (equation 8)

$$\frac{de_s}{e_s} = .026 + .0025 + .006 + 0.0125$$

$$= .04$$

$$= 4.0 \text{ percent}$$

Experimental variation in the measurement of K was less than ± 1.0 percent and therefore, the error involved is believed to have been much less than that indicated for K in the above analysis. The error in measurement of e_s is believed to have been twice that in K or ± 2 percent. This is based upon the reproducibility of the results.